# HANDBOOK OF CERAMICS, GLASSES, grasses AND DIAMONDS

diamond

Charles A. Harper Editor-in-Chief

Technology Seminars, Inc., Lutherville, Maryland

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## HANDBOOK OF CERAMICS, GLASSES, AND DIAMONDS

### **PREFACE**

An understanding of materials and their processing and final properties, while not always fully appreciated, is absolutely critical to the design and manufacture of products and to their performance and reliability. Although this has always been fundamentally true, the demands of modern high-technology products frequently make materials the critical limiting factor not only for success in today's products but also for success in achieving the next generation. This is, of course, a constant and continuing goal. A review of recent publications will show that modern materials technology has been well addressed for some groups of materials but not for ceramics, glasses, and diamonds. It is, therefore, the object of this handbook to present, in a single source, all the fundamental information required to understand the large number of materials and material forms, and to provide the necessary data and guidelines for optimal use of these materials and forms in the broad range of industry products. At the same time, this handbook will be invaluable to industry in acquainting its specialists with product requirements for which they must develop, manufacture, and fabricate materials and forms made with ceramics, glasses, and diamonds.

A companion to my other series handbooks, namely, Handbook of Materials for Product Design, Modern Plastics Handbook, and Handbook of Plastics, Elastomers, and Composites, this Handbook of Ceramics, Glasses, and Diamonds has been prepared as a thorough sourcebook of practical data for all ranges of interests. It contains an extensive array of property and performance data, presented as a function of the most important product variables. Further, it presents all important aspects of application guidelines, fabrication-method trade-offs, design, finishing, performance limits, and other important application considerations. It also fully covers chemical, structural, and other basic material properties. The handbook's other major features include an extensive appendix of material properties and suppliers, a thorough and easy-to-use index, and very useful end-of-chapter reference lists.

The chapter organization and coverage of the handbook is equally well suited for reader convenience. The first four chapters are devoted to ceramics, the following three to glasses, and then one chapter devoted to the important roles of ceramics and glasses in microelectronics, and a final chapter devoted to industrial diamonds. In both the ceramic and glass set of chapters, and also in the diamond chapter, the materials presented cover all areas of the subject, including fundamentals, material properties and applications, processes, and the like. As such, they are oriented to have subjects useful for all areas of interest, from research and development to processing, product design, application, and other specialist areas. Materials covered range from general purpose to advanced high-performance product applications.

As will be evident by a review of the subject and author listings, I have had the good fortune to be able to bring together a team of outstanding chapter authors, each with a great depth of experience in his or her field. Together, they offer the reader a base of knowledge as perhaps no other group could. Hence, I would like to give special credit to these authors in this preface. Also, I would like to give special credit to *Ceramic Industry Magazine*, and

Editor Christine Grahl for the material presented in the appendix. This is indeed an excellent addition to this *Handbook of Ceramics, Glasses and Diamonds*.

Reader comments will be welcomed and appreciated.

Charles A. Harper Technology Seminars, Inc. Lutherville, Maryland

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Appendix A.1 Index I.1

#### **CHAPTER 1**

# CERAMIC MATERIALS AND PROPERTIES

Allen B. Timberlake

Consultant

#### 1.1 INTRODUCTION

The numerous branches of ceramics technology are frequently classified as either *traditional* or *advanced*. Traditional ceramics usually include the older technologies, such as brick, china, concrete, and whiteware. Advanced ceramics, also called *fine* ceramics by Saito¹ and Norton,² are generally those where various methods are used to enhance the properties—to make them harder, stronger, or more chemical resistant, for example. Emphasis in this chapter is given to advanced ceramics.

This chapter is intended to provide a convenient compilation of many properties of the materials discussed in other chapters of the book. Properties of interest to workers using ceramics in structural as well as in electronic applications are listed. Several works have been used extensively, including Harrison and Moratis, Mattox, Schwartz, Buchanan, and Saito. In addition, industrial sources including Coors Ceramics, Kyocera, DuPont Electronics, and Norton Diamond Film have been used.

#### 1.1.1 Definitions of Tabulated Properties

1.1.1.1 Units and Conversion Factors.<sup>7</sup> The properties tabulated in this chapter are defined in this section. The units of measure used in the tables are those used in the article from which the data were taken, unless otherwise indicated. Since workers in the various branches of ceramics technology use different systems of units in their publications—e.g., cgs metric, mks metric, International (S.I.), English, or U.S. Conventional—Table 1.1 lists and defines the units of the International System. Table 1.2 provides factors for converting among the various systems.<sup>7</sup> In cases where it seems desirable to convert data found in a source from one system to another for consistency in a table, the converted data will be placed in brackets, { }. The properties are grouped according to whether they are mechanical, thermal, or electrical.

 TABLE 1.1
 Derived Units of the International System (SI)

Quantity	Name of unit	Unit symbol (if different from basic form)	Unit in terms of base units
Area	square meter		m <sup>2</sup>
Volume	cubic meter		$m^3$
Density	kilogram per cubic		kg/m <sup>3</sup>
	meter		
Force	newton	N	$kg \cdot m/s^2$
Pressure	newton per square meter, pascal	N/m <sup>2</sup> , Pa	$kg/(m \cdot s^2)$
Power, heat flux	watt, joule per second	W, J/s	$kg \cdot m^2/s^3$ $m^2/(s^2 \cdot K)$
Heat capacity	joule per kilogram per kelvin	J/(kg·K)	
Thermal	watt per meter per	$W/(m \cdot K)$ ,	$kg \cdot m/(s^3 \cdot K)$
conductivity	kelvin, joule-meter per second per square meter per kelvin	$J \cdot m (s \cdot m^2 \cdot K)$	

 TABLE 1.2
 Factors for Converting SI Units to U.S. Customary or English Units

Quantity	SI unit	U.S./English unit	To convert SI to English multiply by:	To convert English to SI, multiply by:
Area	square meter, m <sup>2</sup>	square foot, ft <sup>2</sup>	10.76391	0.09200304
Volume	cubic meter, m <sup>3</sup>	cubic foot, ft <sup>3</sup>	35.31467	$2.831685 \times 10^{-2}$
Mass	kilogram, kg	pound, lb	2.204623	0.4535924
Density	kilogram per cubic meter, kg·m <sup>-3</sup>	pound per cubic foot, lb/ft <sup>3</sup>	0.06242795	16.01847
Force	newton, N	pound force, lbf	0.2248089	4.448222
Energy	joule, J	British thermal unit, Btu	$9.478172 \times 10^{-4}$	1055.056
Energy	kilowatt-hour, kwh	British thermal unit, Btu	3412.142	$2.930711 \times 10^{-4}$
Pressure	Pascal, Pa	pound per square inch, lb/in <sup>2</sup>	$1.450377 \times 10^{-4}$	6894.757
Power, heat	watt, joule per second	Btu per hour, Btu/h	0.2939711	3.9016949
Heat capacity	joule per kilogram per kelvin	Btu per pound per Fahrenheit degree	$2.389 \times 10^{-4}$	$4.1868 \times 10^3$
Thermal conductivity	watt per meter per kelvin, W/m · K	Btu-foot per hour per square foot per Fahrenheit degree, Btuft/(h · ft² · F°)		1.730735

TABLE 1.3 ASTM Property Test Methods

Properties	ASTM test methods	
Physical		
Specific gravity	C-329, C-20	
Porosity	C-373	
Flexure strength	C-674	
Hardness	C-730, E-18	
Fracture toughness		
Thermal		
Expansion coefficient	F-228, C-359	
Thermal conductivity	C-408, C-177	
Shock resistance	D-116	
Electrical		
Dielectric constant	D-2149, D-150,	
and dissipation	D-2520	
factor		
Dielectric strength	D-149	
Electrical resistivity	D-257, D-1829	

Table 1.3 lists many ASTM methods of measurement for the properties of most interest to users of ceramics.

#### 1.1.1.2 Mechanical Properties

**Density.** The mass per unit volume of a material is its density. The term is often used synonymously with *specific gravity*, a unitless quantity that is the ratio of the density of the material to the density of pure water at 4°C. The two quantities are numerically identical in the SI system, but are quite different in the English system.

**Elastic Modulus or Young's Modulus.** When a rod of length l and cross-sectional area A is subjected to a tensile force F, the rod will undergo an increase in length  $\Delta l$  according to the formula

$$\Delta l = Fl/AE \tag{1.1}$$

where E is a property of the material known as *Young's modulus*. Young's modulus, then, is the relationship of stress to strain, i.e., the fractional change in dimension caused by an applied force. Young's modulus can also be determined by measuring the bending of a rod by a force applied to the midpoint of the rod supported at both ends.

**Shear or Rigidity Modulus**. When successive layers of material are moved or sheared by tangential surface force or a torsional force, the magnitude of strain is determined by the shear modulus or modulus of rigidity. The angular strain,  $\theta$  radians, induced in a rod of radius r, length l, by a torque C is given by

$$\theta = 2Cl/\pi r^4 M \tag{1.2}$$

where M is the modulus of rigidity of the material.